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# Multi-Objective Optimization for Combined Heat Power Operations considering Flexibility, Costs and Environmental Emissions

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**Abstract**. Optimal operation of a combined heat and power (CHP) system proves to be a challenge. This is because CHP systems could be operated in several alternative configurations. In fact, each technology may have different heat and electricity outputs, costs, emissions and flexibilities. To address such challenge, operational optimization must be considered. In this paper, a mathematical optimization model was developed to optimise cost, carbon dioxide emissions and flexibility for a CHP system operation to meet increased energy production requirements. The developed model employs multi-objective optimization to determine a trade-off between costs, carbon dioxide emissions and flexibility. To demonstrate the proposed approach, a multi-fuel CHP case study was solved. Results indicate that a trade-off CHP configuration that achieves the best possible balance between costs, emissions and flexibility was determined.

## 1. Introduction

Combined heat and power (CHP) systems can be comprised of various technologies that utilize a wide range of fuels. These fuels are utilized by technologies like boilers to produce pressurized steam. The produced steam would then be used to generate electricity via steam turbines. Aside from this, fuels could also be combusted in gas turbines and/or gas engines to produce power and exhaust heat. This exhaust heat can then be recovered and used to produce pressurized steam via heat recovery steam generators (HRSG). The various technologies mentioned indicate that a CHP system could be operated in several configurations. This is evident as each technology differs in terms of heat and electricity outputs, costs, emissions and flexibilities. In addition to this, the choice of technologies would depend heavily on the fuel chosen too. In this respect, it would be a challenging task to decide which technology would be best to operate in a CHP system. To address this challenge of operating a CHP system, operational optimization must be considered. This involves adjusting and optimizing CHP operations to minimize cost, minimize carbon dioxide emissions and maximize flexibility.

There are vast amounts of works done to optimize economic and environmental performance of CHP operations. For example, Majidi et al. [1] proposed a robust optimization-based framework for economic operation of CHP system under severe uncertainties with the supplementation of demand response programs to address seasonal electrical and heating demands. Next, Shaabani et al. [2] have proposed a real-time scheduling model that can be integrated and used into energy management systems that are equipped with CHP systems. Shaabani et al. [2] applied an optimization technique based on time-varying acceleration particle swarm optimization (TVAC-PSO) to a 7-unit CHP test system for optimizing economic emission dispatch. Monte Carlo method was also used to solve the stochastic model to provide a real situation [3]. However, these works did not consider flexibility as part of the optimization criteria in CHP operations.

Several studies have been presented on operational optimization considering the flexibility of systems. For example, Lai and Hui [4] demonstrated a flexible CHP design that can handle periodical deviations in utility demand for a commercial building complex. Here, various modifications to the process such as over-sizing, thermal storage and flexibility reallocation have been considered to enhance the system's feasibility and flexibility [4]. More recently, Foong et al. [5] presented a hybrid approach that combines mathematical programming as well as graphical approach to work out and evaluate a palm oil mill case study [6] in Malaysia. This hybrid approach employs Input-Output Model (IOM) that optimizes the palm oil mill for given set of conditions. The approach also employs feasible operating range analysis (FORA) [7] to investigate the flexibility and utilization of the design [5].

Despite the significance of the previously mentioned works, many of them present either single or dual objective optimization approaches. For instance, most mentioned works only focus on economic performance of CHP systems by minimizing costs or maximizing profits. Meanwhile, other papers focused on flexibility while considering either economic performance or environmental performance. Evidently, limited work has been found to address all costs, environmental impact and flexibility simultaneously.

## 2. Problem Statement

Operating a CHP system comes with its own set of challenges. This is especially the case when the CHP system involves the usage of different fuels and technologies. Fuels have unique cost implications, calorific values and carbon dioxide equivalent emissions. Meanwhile, each technology in a CHP system would differ in terms of efficiencies, operating costs (i.e. operations and maintenance, start-up and shutdown costs) and fuel compatibilities. These factors lead to many possible CHP system configurations, thus increasing the complexity and difficulty of deciding on an optimal CHP operation. In fact, it is desirable to have an operation that has minimal costs, minimal carbon dioxide emissions but with high flexibility. However, these aspects are contradictory in nature. A method to approach this complexity is through mathematical optimization. In this work, the objective is to develop an operational optimization model that can determine a trade-off configuration for the CHP system while considering contradicting variables such as flexibility, cost and carbon dioxide emissions.

## 3. Mathematical Model

To address the problem stated in Section 2, mathematical equations are formulated to model the behavior and properties of a typical CHP system. These behaviors and properties would include mass and energy balances, efficiencies, operating conditions, etc [8]. From here, fuzzy multi-objective optimization (equations 1 – 4) is employed to determine the trade-off (given by $\lambda$) between the contradicting variables. Fuzzy multi-objective optimization assumes each objective considered is fuzzy goal that is subjected to a set of upper and lower limits. In this work, the fuzzy goals are cost, emission and flexibility. The cost objective in equation (1) considers fuel cost, operational cost and start-up cost and shutdown costs. Equation (2) factors environmental emission by considering different fuels. Finally, flexibility of the CHP system towards changes in demands is considered in equation (3).

$$(\mathrm{C}^{\max} - C) \Big/ (\mathrm{C}^{\max} - \mathrm{C}^{\min}) = \lambda^{C} \tag{1}$$

$$(\mathrm{Em}^{\max} - Em) \Big/ (\mathrm{Em}^{\max} - \mathrm{Em}^{\min}) = \lambda^{Em} \tag{2}$$

$$\left(F - \mathrm{F}^{\min}\right) \Big/ \left(\mathrm{F}^{\max} - \mathrm{F}^{\min}\right) = \lambda^{F} \quad (3)$$

$$\lambda^{C}, \lambda^{Em}, \lambda^{F} \geq \lambda \quad (4)$$

$\mathrm{C}^{\max}$, $\mathrm{Em}^{\max}$ and $\mathrm{F}^{\max}$ are the upper limits for cost, emissions and flexibility index respectively. Meanwhile, $\mathrm{Em}^{\min}$ and $\mathrm{F}^{\min}$ represent the lower limits for these three objectives. These upper and lower limits of cost, emissions and flexibility index can be obtained in several steps. Firstly, the upper limits of flexibility index, cost and emission can be obtained by maximising the flexibility index, *F*. Next, the lower limits of flexibility index and cost can be obtained by minimising cost, *C*. The lower limit of emissions can be obtained by minimising emissions, *Em*. Once the values for the limits have been obtained, the trade-off variable, $\lambda$ shown in equation (4) is maximized. When $\lambda$ is maximized, *C* and *Em* variables would be minimized to achieve maximum satisfaction for cost and emission objectives ($\lambda^{C}$ and $\lambda^{Em}$ get closer to 1). As *C* and *Em* variables are minimized, the corresponding values for *F* would be much lower as well. This however, is not desired. To counteract this, equation (3) allows *F* to be maximized when $\lambda$ is maximized. Such mathematical formulation addresses the contradicting nature between cost, emission and flexibility as well as allow for a trade-off to be established.

## 4. Case Study and Results

This case study considers a typical CHP system operation involving multiple technologies and fuels. This CHP system contains a total of 2 stoker boilers, 2 fluidized bed boilers, 1 gasifier and 10 prime movers consisting of gas turbines, gas engines and steam turbines. The CHP system is currently operating at a baseline rate with 13 MW of electricity generation and its corresponding 30.1 kg/s of low-pressure steam output. This CHP system is expected to adjust operations to meet changes in electricity and low-pressure steam demands. The electricity and low-pressure steam demands are expected to increase by 60% and 50% from baseline rates respectively. The aim of this case study is to determine an operation strategy for the CHP that trades-off on cost, emissions and flexibility to meet the change in demand expected for the CHP. To do that, four scenarios were considered. Three scenario involves minimizing cost, minimizing emissions and maximizing flexibility index respectively. The results obtained from each of these three scenarios would be upper and lower limits for the fourth scenario (as shown in equations (1 – 3)).

To solve each scenario, a mixed integer linear programming (MILP) model was developed. This MILP model was solved within 2 seconds of CPU time via LINGO v17.0 using ASUS G551 JM laptop with Intel Core i7 (2.50 GHz) processor and 8 GB RAM. The model formulated for this case study consists of 273 total variables, 45 integer variables and 260 constraints. Results for each scenario in this this case study are shown in Figure 1 and Table 1.

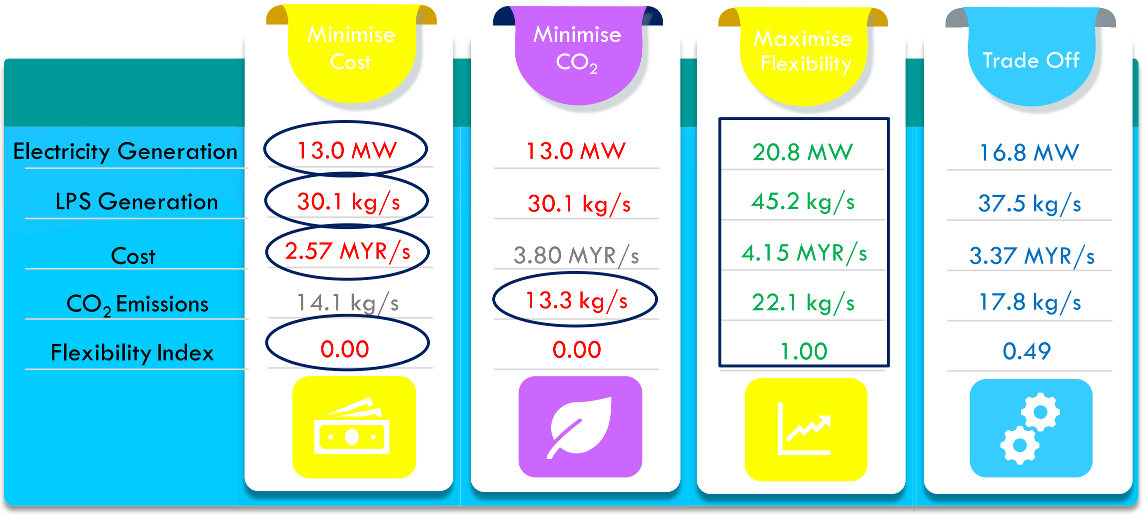


**Figure 1.** Results of Case Study

It is worth noting that in Figure 1, results that are circled represent the lower limits. The results within the rectangular outline in Figure 1 however, are the upper limits. Aside from this, Figure 1 shows that the configuration in the trade-off scenario has an output of 37.5 kg/s of low-pressure steam and generated electricity of 16.8 MW. Aside from this, the system was able to meet 49% of the change in demand, resulting in a flexibility index of 0.49. This indicates partial flexibility towards changes in demand. The overall cost to operate the system using this configuration was determined to be 3.37 MYR/s. The resultant CHP configuration for the trade-off design is shown in Table 1. As compared to other scenarios (i.e., minimized cost, minimized emissions, and maximized flexibility), the trade-off configuration evidently offers a balance between cost, emissions and flexibility for CHP operations.

**Table 1.** Summary of Technologies Chosen for CHP Operation in Trade-off Case

| Technology | Available in CHP | Chosen for CHP Operation |
|---|---|---|
| Stoker Boilers | 2 | 2 |
| Fluidized Bed Boilers | 2 | 2 |
| Gasifier | 1 | 0 |
| Gas Turbine | 3 | 1 |
| Engines | 2 | 0 |
| Steam Turbines (High Pressure) | 3 | 3 |
| Steam Turbines (Low Pressure) | 2 | 2 |

## 5. Conclusion

A mathematical optimization approach was presented to optimize the operation for a CHP system considering cost, carbon dioxide emissions and flexibility. The approach addressed the complexity of operational optimization due to the vast number of possible CHP system configurations. In addition, it employed fuzzy optimization as an approach to simultaneously address contradicting objectives, namely cost, carbon dioxide emissions and flexibility. Fuzzy optimization determined the CHP configuration that provides a trade-off between cost, carbon dioxide emissions and flexibility. Technology start-up and shutdown costs have also been taken into consideration through programming of technology start-ups and shutdowns on top of cost for fuel as well as operating and maintenance costs. To illustrate the proposed approach, a CHP system case study was solved. To test the flexibility of the CHP system, it is subjected to changes in demand for its low-pressure steam output and electricity generation. In the case study, four scenarios were considered. The first scenario determines the configuration that minimize overall cost. The second scenario minimizes carbon dioxide emissions while the third maximizes flexibility of the CHP system. Based on values obtained from these three scenarios, the fourth scenario employs fuzzy optimization to determine a trade-off configuration that satisfies the contradicting objectives. From the results of the case study, a CHP design that is a trade-off between costs, emissions and flexibility was established.

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